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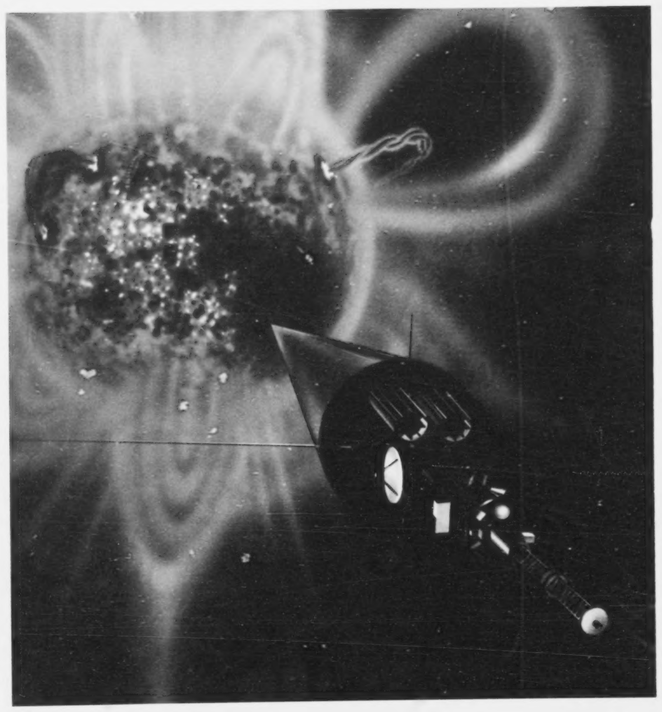
SOLAR PROBE



Report for the Space Science and Applications Advisory Committee

Jet Propulsion Laboratory

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Mission Overview

The Solar Probe will be an initial reconnaissance mission to the last major solar system body that remains unexplored. Just as the Voyager spacecraft returned stunning new scientific insights about the outer planets, Solar Probe will be a voyage of discovery to the center of our solar system — a visit to our star, the Sun. No previous spacecraft has traversed the region within 0.3 AU of the Sun. Solar Probe, by passing within 3 solar radii of the Sun's surface, will answer long-standing, fundamental questions such as: What heats the solar corona? What accelerates the solar wind? Where does the solar wind come from? and What mechanisms accelerate, store and transport energetic charged particles? These questions cannot be answered in any way other than by a close encounter with the Sun. Thirty years of attempts have demonstrated aptly that all remote-sensing techniques have limitations and ambiguities that prevent definitive knowledge. This knowledge, once obtained, will additionally have direct application to similar processes that operate near other stars.

The Solar Probe, besides exploring the Sun, will also lead to progress in plasma physics. The study of nonlinear plasma waves and plasma turbulence is challenging and demanding research. Advances in our theoretical understanding are often stimulated by observing unpredicted phenomena. The encounters with Comets Giacobini–Zinner and Halley revealed collisionless nonlinear waves with features that still challenge explanation. The solar corona provides a plasma regime found nowhere else in the solar system in which observations of strongly nonlinear waves and plasma turbulence will advance our understanding of wave–particle and wave–wave coupling in a collisionless plasma.

Solar Probe will also explore the interplanetary dust cloud. The dust experiment aboard Solar Probe will be able to determine relative contributions to the cloud that surrounds the Sun from the various sources in our heliosphere; the slow grinding of asteroids through mutual collisions within the belt between Mars and Jupiter; the outgassing (dust and neutrals) of short- and long-period comets, and the inflow of interstellar grains. The experiment will also be able to determine whether or not discrete circumsolar dust belts exist between 4 and 10 solar radii, a long-standing controversy in the field.

National Academy of Science committees, in the Field report (Astronomy and Astrophysics for the 1980s, *NAP, 1982), the Krimigis report* (An Implementation Plan for Priorities in Solar System Space Physics, *NAP, 1985), and the Scarf report* (Space Science in the Twenty-First Century — Solar and Space Physics, *NAP, 1988), have recognized the importance of Solar Probe. In response, Solar Probe has been in the NASA strategic plan since 1988. More recently, the Space Physics community convened at two workshops in 1990 to plan the sequence of Space Physics missions for the next twenty years. The results are published in two separate Space Physics Division workshop reports (Fox and Siscoe, 1990; Siscoe, 1991). The workshops recommended that the Solar Probe mission should be the highest priority for a Space Physics major mission new start after 1995.*

Mission Design

Figure 1 is an illustration of the near solar portion (±30 days of perihelion) of a typical Solar Probe trajectory to the Sun that relies on a Jupiter gravity assist required to provide the very large velocity change (~13 km/sec) necessary to reach 4 R_s from the Sun's center. Jupiter's gravity assist also changes the inclination of the Solar Probe orbit to 90°. Thus, the final orbit will have a perihelion of 4 R_s, an aphelion of about 5 AU and an orbit inclination of 90°. The orbit is phased so that at the time of encounter, the plane of the orbit is orthogonal to the Earth–Sun line so that continuous radio communication is maintained. Perihelion occurs in the ecliptic plane above the west limb of the Sun; thus, the solar regions over which Solar Probe will fly can be seen from the Earth prior to perihelion passage. The large aphelion is defined by Jupiter and results in a final orbital period of about 4 years. The mission and spacecraft systems have been designed such that Solar Probe has a minimum lifetime of two perihelion passes (about 8 years) plus the option of an extended mission. During each pass, Solar Probe spends 10 days inside the unexplored region within 0.3 AU of the Sun; the pole-to-pole passage time is 13 hours. A conical thermal shield kept pointed at the Sun during perihelion passage provides an environment with normal temperatures (20–30°C) for the spacecraft payload.

Scientific Investigations Summary

The in situ experiment package aboard the Solar Probe will return information that cannot be obtained remotely. The experiments include the following: 1) a Three-Dimensional Plasma Experiment that measures fluxes of thermal and suprathermal electrons and a mass-per-unit charge spectrometer that measures fluxes of thermal and suprathermal ions; 2) a Magnetometer with time resolution of 40 ms; 3) a Plasma Wave Experiment with electric and magnetic sensors covering the frequency range from 10 Hz to 25 MHz; 4) a Suprathermal Ion Mass and Charge Analyzer covering the energy range 0.01–200 keV/Q and mass range from 1–60 amu; 5) a Medium Energy Particle Analyzer that detects 0.02–10 MeV/amu ions in the mass range 1–60 amu and 0.01–1 MeV electrons; 6) a High Energy Particle Experiment that measures 5–100 MeV/amu nuclei in the mass range 1–60 amu and 1–10 MeV electrons; 7) a Coronal Imager (white light); 8) a combined X-Ray, Neutron, γ-Ray Experiment, and 9) a Dust Experiment using an impact plasma sensor that measures masses and velocities of dust grains more massive than 10^{-17} g.

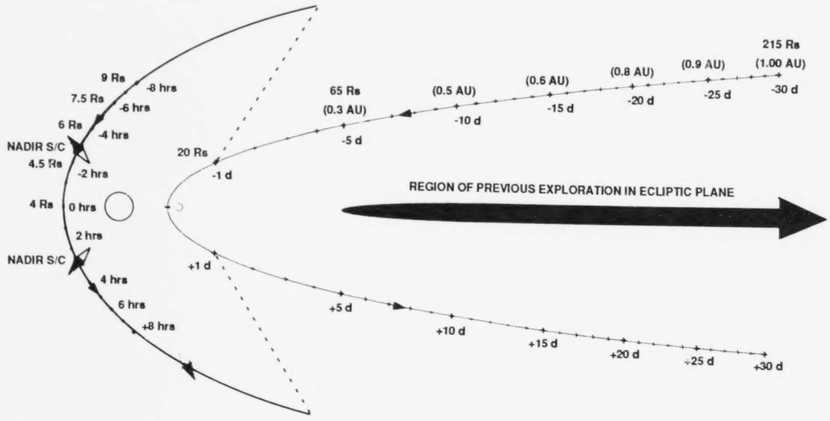

Figure 1: Solar Probe Perihelion Trajectory

Spacecraft Design

The spacecraft (Figure 2) has a conical thermal shield of carbon–carbon construction kept pointed toward the Sun within the inner solar system. This shield protects the payload from the intense heat of the Sun, ensuring experiment operations at room temperatures. A three-axis attitude control system maintains spacecraft orientation. Field-of-view scanning is provided by the individual experiment packages as needed. Power is provided by Radioisotope Thermoelectric Generators (RTGs), and communications are provided by Ka-band telemetry to reduce coronal interference.

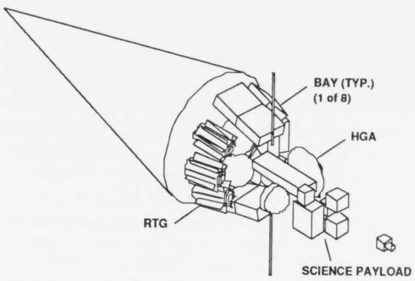

Figure 2: Solar Probe Spacecraft

Mission Expectations

Solar Probe is a mission of exploration and discovery in a region near the Sun that has never previously been directly investigated. Major advances and surprises in our understanding of the planets resulted from the first planetary exploratory missions; Solar Probe should similarly revolutionize our understanding of the corona and the solar wind. The first in situ measurements of coronal particles and fields will provide definitive discriminators among many currently proposed models of processes that shape the structure and dynamics of the outer corona and solar wind. In addition, observation of the development of turbulence, nonlinear wave processes, plasma heating and particle acceleration in the corona will advance our understanding of these areas of plasma physics in a new regime that is neither duplicated by Earth-based laboratories nor by previous space exploration. It will also fill the last gap in our knowledge of the terrestrial response to the solar output and provide insight for interpreting observations of general stellar envelopes.

I. Scientific Merit

I.A. Key Issues

What are the key scientific issues being addressed by the mission?

How significant are these issues in the context of science?

To what extent is the mission expected to resolve them?

The primary focus of Solar Probe will be to address several outstanding fundamental scientific questions that bear on the structure and dynamics of the outer solar atmosphere. This region remains the last unknown link that couples the solar output to the terrestrial environment. However, the trajectory required for a close solar encounter also provides a mission of opportunity to conduct other scientific investigations as well. We summarize the key scientific issues below.

What heats the solar corona?

The defining characteristic of the solar corona that sets it apart from the lower atmospheric layers is its million-degree temperature; this was first recognized in the early 1940s. This temperature is much higher than that of the dense photospheric gas below (6000 K), so that radiative and conductive losses from the corona must be balanced by some nonradiative energy source. Initial proposals for an energy source focused on mechanical heating by waves generated by convective turbulence present just below the photosphere. Although after 45 years of searching, there is as yet no experimental confirmation and this mechanism cannot be ruled out. Neither is there definitive evidence to support the currently popular heating mechanism, energy input from the broad spectrum of microactivity observed within the chromosphere–corona transition region. Such evidence cannot be provided by remote observations because of two separate factors: line-of-sight observations of the disk are biased to favor the lowest, densest layers at a given temperature, and observations of the outer corona necessarily integrate over a very large volume, thus preventing resolution of individual, small-scale structures. However, these structures are thought to cause the heating of the corona. In situ observations by the Solar Probe can provide definitive discriminators.

What accelerates the solar wind?

The simplest and best understood case of solar wind flow is the expansion from a coronal hole to the high-speed solar wind observed near Earth. The decreasing density with increasing distance produced by solar gravity causes a pressure gradient that accelerates the flow upward. The flow is subsonic near the Sun, but as the speed increases, it becomes supersonic with increasing distance. However, calculated flows that match measured conditions at the base of the corona fail to reproduce observations at 1 AU. All models that have been devised to correct this deficiency require extended heating and/or momentum addition to the outflowing plasma. The form and distribution of these additions are not known. Examples that have been suggested include energy addition through jets of upward moving gas accelerated at lower altitudes by flare-like processes (Figure 3) and momentum addition through secondary, jet-driven magnetohydrodynamic (MHD) waves and diamagnetic $\underline{J} \times \underline{B}$ forces. Remote sensing cannot determine the energy flux in waves, electron heat flux or multiple ion beams; and line-of-sight problems prevent observations of energetically important small-scale processes. In situ observations will determine the processes that heat and accelerate the solar wind.

Where does the solar wind originate?

All observations of the solar wind have been obtained beyond the orbit of Mercury. Observed flows are classified into two major categories: high-speed and low-speed solar wind. Attempts to locate the origins of these flows in the low corona have failed due to a lack of knowledge of the evolving bulk speed as a function of height above the coronal base. The possibility of time-dependent acceleration, nonradial flows as evidenced by a pronounced skewness of some coronal streamers seen in eclipse photographs (Figure 4) and the Sun's rotation, all combine to yield considerable uncertainty in the coronal footprints of measured solar wind volumes. Two exceptions (Figure 5) are: identification of the large-volume high-speed flows with the large-area coronal holes (because small alignment uncertainties do not prevent identification), and the magnetic sector boundaries with the streamer belt that encircles the Sun. However, several other coronal structures may contribute to the low-speed solar wind, such as the general quiet corona and regions of magnetic activity. Matching observed solar wind flows with such sources is not now possible because of cumulative uncertainties in tracing back to the source; these errors can be reduced to insignificance by a Solar Probe close flyby.

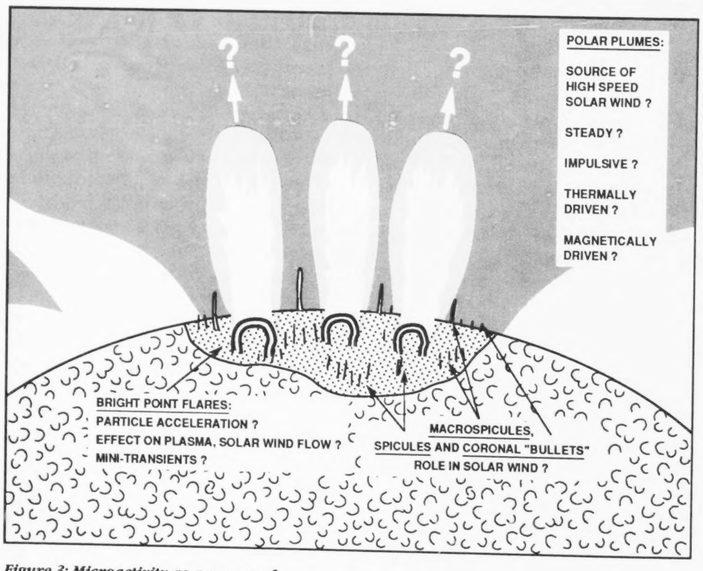

Figure 3: Microactivity as a source of solar wind acceleration

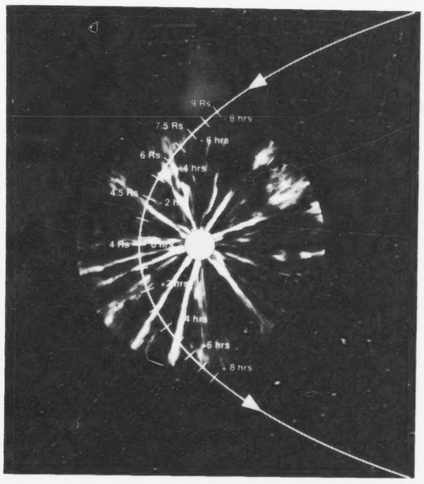

Figure 4: Enhanced Eclipse Picture

What mechanisms accelerate solar energetic particles?

Many possible mechanisms are known from studies in interplanetary space and at planetary magnetospheres. One such mechanism, acceleration due to reconnection between regions of oppositely directed magnetic field, is depicted in Figure 6. Jets of heated, shocked gas are accelerated away from the current sheet. Particles can be accelerated to high energies either within the current sheet by traveling along the electric field (perpendicular to the plane of the Figure) or by electric and magnetic fields associated with the shocks. The mix that leads to acceleration of electrons to hundreds of MeV and protons to several GeV in seconds (as inferred from a few γ-ray flares) is a mystery. So are the events that yield an anomalously high abundance of He–3 and other heavy ions. Theory indicates these mechanisms can be discriminated by observing at energies below about 1 MeV. Near-solar observations are required for this discrimination because velocity dispersion and energy diffusion due to passage of the particles through overlying strongly turbulent coronal layers obscure the signature.

What is the seed population for particle acceleration?

A continuing source of difficulty has been our inability to predict the intensity of solar energetic particles at the Earth from observed transient activity on the Sun. Such a capability becomes ever more important as use of space for economic and national security activities, as well as for human exploration, becomes routine. An important part of the problem is that we do not know, nor can we infer from remote-sensing observations, the suprathermal population that feeds the various acceleration processes near the Sun. Particle detectors aboard the Solar Probe can measure these populations directly and thereby provide a definitive answer in a single pass. The seed population on closed field lines can be assessed from the steady-state X-ray background.

What is the efficiency of particle acceleration near the Sun?

Acceleration efficiency provides an essential link to relate the observed energy spectrum of cosmic rays near the Earth and conditions that caused their acceleration within the Galaxy. However, the efficiency for transferring energy from flare plasmas to a few energetic particles cannot be inferred from remote-sensing observations in interplanetary space because an unknown fraction of the accelerated ions remain bound to the Sun by strong magnetic fields. Subsequent γ-ray and neutron emissions resulting from their eventual loss to the atmosphere are often too low in flux to be observed even from a spacecraft orbiting Mercury. However, present observations indicate that small transients occur sufficiently often to allow a determination of the efficiency from a single perihelion passage of the Solar Probe using secondary γ-rays, hard X-rays and neutrons as proxies for the magnetically bound component.

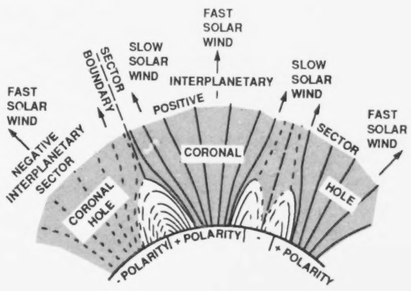

Figure 5: Model of large-scale coronal structure and association with solar wind features

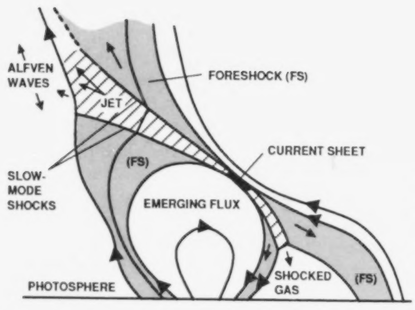

Figure 6:
Reconnection event

What is the nature of plasma turbulence near the Sun?

Observations of the scintillation of radio signals after passage through the solar corona have provided the clearest indication to date for strong plasma turbulence within a spherical region at distances of less than 30 solar radii from the Sun (Figure 7). The Solar Probe offers the exciting possibility of probing a state of low-beta (the ratio of plasma pressure to magnetic pressure) plasma turbulence that is qualitatively different from any other turbulent plasma in the solar system. MHD and plasma turbulence models have major theoretical uncertainties. Specifically, damping by wave–particle interactions provides a loss mechanism not included in present models based on incompressible magnetohydrodynamics with viscous and ohmic dissipation. Measuring the long-term evolution of the wave field from the solar source region to the outer heliosphere will improve our understanding of how the dynamics of the turbulence is determined by wave–wave interactions, damping from wave–particle interactions and outward transport.

What nonlinear wave processes occur near the Sun?

Nonlinear plasma wave physics is sufficiently complex that observations have historically led theory in identifying important problems. An example is provided by waves generated by the pickup of cometary H_20 group ions (see Figure 8). Wave steepening processes lead to: the formation of nonlinear whistlers with $\Delta\vec{B}/B_0 \sim 2$, a foreshortening of the phase-rotation portion of the wave, a trailing portion of the wave which has little or no phase rotation and occasional reversals in phase rotation within the wave. None of these features are predicted by linear theory. Large amplitude, nonlinear waves can steepen into "shocklets," leading to wave–particle interactions such as shock-drift type acceleration at the steepened wave fronts and particle mirroring from both the shock and the compressional portions of the wave. These waves may propagate at much higher speeds than predicted by MHD theory and therefore may be considerably more effective in accelerating particles. The nonlinear wave evolution processes discovered in the Comet Halley and Comet Giacobini–Zinner encounters of 1985–1986 still stand today as a challenge to theoretical understanding. It is known from both theory and observations that large amplitude waves are present in the corona; they are expected to play an important role in heating the solar wind. Observations of these waves are therefore important for understanding dissipation processes that shape the ambient thermal and suprathermal particle populations; they are also expected to provide new and unexpected insights into modes of interaction possible between waves and trapped particles. Important, unanticipated advances in our understanding of plasma physics came from the cometary missions. Similar progress in this important area can be expected from the unparalleled laboratory of the solar corona.

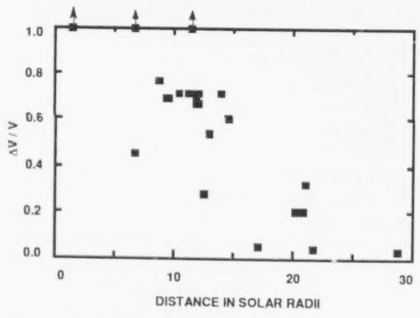

Figure 7: Radio scintillation observations of coronal velocity fluctuations

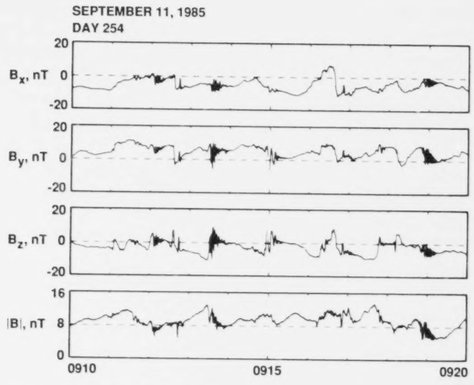

Figure 8: Cometary Plasma Wave: magnetic field data

What processes regulate plasma and energetic particle transport in the corona?

Plasma and energetic particle transport are essential processes that shape the solar envelope, and stellar envelopes as well. One of the most important transport processes is thermal conductivity. The Sun, like all stars, is much hotter than the neighboring interstellar medium. Thermal conductivity mediated by binary Coulomb interactions is sufficiently high that substantial energy can be transferred from the Sun to considerable distances. Indeed, early analyses of the extended solar envelope demonstrated that this property of a collisionless plasma inevitably leads to a supersonic expansion. Thermal conductivities based on Coulomb collisions imply that conducted heat should dominate the energy flux near the Sun, yet measurements of the heat flux at the innermost location attained by an in situ space probe, HELIOS with perihelion at 0.3 AU show it is negligible compared to the convected energy flux. Something very drastic must occur between the temperature maximum in the low corona and 0.3 AU to reduce this flux to insignificance. The mechanism is not known, but the effect on the flow is major. Theory suggests that microinstabilities limit heat flux, but this is not well understood and predictions of the mode of dissipation of this heat flux are not possible. The relative importance of heat flux and competitive energy transport mechanisms in the corona and solar wind are thus unknown. Resolution of these issues will result from the plasma and field data recorded during a single perihelion passage of the Solar Probe.

What are the origins and loss mechanisms of interplanetary dust grains?

Objects in the solar system originated from interstellar gas and dust. The dust now present in the solar system comes from both pristine and processed sources. Some meteoroids (or cosmic dust grains) are known to come from comets. Other dust grains come from collisions between asteroids or directly from interstellar space. What is not known are the relative and absolute strengths of these sources and how they depend upon location in the solar system. Loss mechanisms for interplanetary dust grains are also not well understood. Grain–grain collisions make the dust particles finer and finer until radiation pressure ejects them (as beta meteoroids) from the solar system. These grains then become interstellar grains, completing a "dust to dust" cycle. Near the Sun, dust particles spiraling inward under the influence of the Poynting–Robertson effect and solar wind drag are also vaporized.

Observations of the zodiacal light obtained using HELIOS indicate that the spatial dust density increases inversely with heliocentric distance as $R^{-1.5}$ (at least to 0.1 AU). Little is directly known about the dust density inside 0.1 AU. However, according to our current understanding of collisional and drag losses, dust grain lifetimes of less than 200 years are predicted for all grains less than 100 grams at 0.1 AU. These lifetimes will be even less close to the Sun where discrete dust rings (between 4 and 10 solar radii) have been reported (see Figure 9). Sources sufficient to support these losses are not

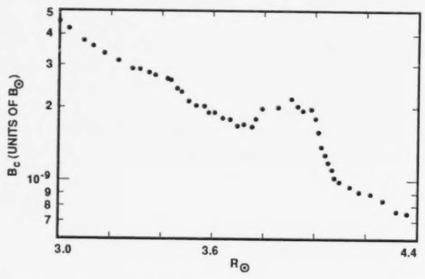

Figure 9: Thermal emission features of corona, 11/12/66

presently known, highlighting an incompatibility between theory and observations. However, a direct measurement of the density and orbital distribution of dust grains to within 4 solar radii of the Sun's center by the Solar Probe will allow a much better identification of the balance between source and loss mechanisms. The Solar Probe mission will additionally extend our knowledge of dust properties to many unexplored regions of the solar system, thus allowing identification of individual sources and a better understanding of evolution of the distribution. It will explore the heliographic latitudes ranging between 15 degrees at 1 AU and 90 degrees at about 7 solar radii and will determine the relative fluxes of prograde and retrograde orbiting dust over a range of heliocentric latitudes and distances. These measurements will greatly improve the determination of the relative contributions of both long- and short-period comets, and asteroids through mutual collisions, to the zodiacal dust cloud.

I.B. Generality of Interest

Why is the mission important or critical to the proposing scientific discipline?

After more than 30 years of research, many of the most fundamental questions in the disciplines of solar wind and solar energetic particle research remain unanswered. Specific scientific issues were listed and previously discussed. The reason for this impasse is that a very critical region of our solar system, between 3 and 65 solar radii above the Sun's surface, has never been visited. Indeed, Solar Probe explores the inner frontier of the heliosphere for the first time. This region is an essential link in the solar–terrestrial chain, without which we cannot unravel the factors that control coronal heating, solar wind and energetic particle acceleration, plasma and energetic particle transport through the strong turbulence layer that encircles the Sun and the origin and evolution of the dust in the heliosphere.

What impacts will the science accomplished by the mission have on other disciplines?

Progress in all science disciplines enabled by Solar Probe has clear impact on related disciplines in astrophysics, planetary physics, solar physics and magnetospheric physics/space plasma theory. An area of general applicability is astrophysics because of the diverse natures of space plasma and energetic particle processes throughout the universe. Progress in a number of astrophysics subdisciplines during the past 20 years has shown that phenomena in the solar corona and the solar wind have close analogs in astrophysical settings. For example, a large number of all stars, both on and off the main sequence, have chromospheres and coronae. However, only the premain sequence T-Tauri and postmain sequence giants and subgiants are known to support stellar winds. All F through M stars on the main sequence are also thought to support stellar winds from their observed correlation of spin rate, magnetic activity and age, yet their winds are not dense enough to be directly observed.

The two disciplines of Space Plasma Physics and Stellar Astrophysics complement one another in an important way. Whereas a very broad range of stellar environments can be inferred from astrophysical observations, often very little can be learned about detailed structure and dynamics. On the other hand, we have only one stellar environment available in the heliosphere, but we can probe its structure and sort the interrelations of its formative mechanisms in microscopic detail. Such observations not only verify theoretically anticipated processes but often provide considerable surprises. Improved understanding of nonlinear plasma waves, the development of turbulence and consequent wave–particle interactions, shock heating, magnetic reconnection and particle acceleration should provide insight into how these processes occur in related astrophysical settings. Possible areas of application include: 1) the structure and dynamics of stellar coronae; 2) stellar mass loss; 3) the origin and propagation of cosmic rays, and 4) characteristics of low-beta, turbulent, cosmic plasmas.

A further astrophysical application of the Solar Probe is the accurate determination of source locations for cosmic γ-ray bursts using the long spacecraft-to-Earth baseline to other spacecraft with γ-ray detectors.

Is there a potential for closing a major gap in knowledge, either within an important discipline or in areas bridging disciplines?

As mentioned previously, we have very little knowledge about plasma conditions and related processes operating in the unexplored zone to be traversed by Solar Probe, i.e., from 3 to 65 solar radii above the solar surface. This gap in our knowledge prevents us from answering numerous basic questions about the solar wind and corona such as: What heats the solar corona? What accelerates the solar wind? and Where does the solar wind originate? Solar Probe will help expand our understanding of other important questions such as: What mechanisms accelerate solar energetic particles (SEPs)? What is the seed population for the SEPs? What is the efficiency of particle acceleration in the solar environment? and What is the nature of the strong plasma turbulence near the Sun, and how does it affect plasma and energetic particle transport? Some progress has been made in answering questions about coronal structure. The discovery by Skylab of coronal holes was a major step forward, and the SOHO mission should provide an improved definition of plasma conditions in the lower corona that will help constrain models of the structure and dynamics of the upper corona and solar wind. However, progress in answering the foregoing basic questions about the solar wind and corona with remote-sensing techniques alone has been modest; we have many more detailed speculations than 20 years ago, but little more certainty. Another major gap to be filled by the Solar Probe is determining the sources and evolutionary processes of interplanetary dust.

I.C. Potential for New Discoveries and Understanding

Does the mission provide powerful new techniques for probing nature? What advances can be expected beyond previous measurements with respect to accuracy, sensitivity, comprehensiveness and spectral or dynamic range?

Using a specially designed heat shield, Solar Probe can approach within 3 solar radii of the Sun's surface and provide the first in situ observations in a region never before explored. The information to be gained cannot be obtained in any other way. This mission is therefore one of discovery and fundamental new insights. The composition, velocity distribution and abundances of the various particle species will be measured within the corona. In contrast, remote sensing of the corona can only obtain line-of-sight averaged estimates of density and some velocity and magnetic field components. This incomplete description of plasma and field and the complete absence of information about particle distributions in velocity space prevent even a qualitative understanding of the structure, dynamics and evolution of the solar wind. For example, the outward wave energy flux within the corona cannot be estimated with sufficient accuracy to resolve the issue of coronal heating and bulk acceleration, and the energy in nonthermal particles, which may dominate in certain processes, is not even measured at all. Although the X-ray and γ-ray measurements could in principle be done from Earth orbit, microflare activity at the small-scale sizes that may account for much of the coronal heating cannot be detected. To achieve counting statistics (square root of signal to background) comparable to that expected for the Solar Probe at $3R_s$ above the solar surface would require a detector $(214/3)^4$ more massive than the Solar Probe detector, i.e., 10^7 kg, which would cost more than the entire Solar Probe mission. Low energy neutrons cannot be observed at 1 AU because, in addition to the $(214/3)^4$ scaling law, the neutrons spread in distance because of differing speeds and because they decay en route to Earth, further reducing flux by many orders of magnitude. Determination of dust trajectories at high latitudes and in the inner solar system requires an in situ investigation; line-of-sight integrated optical or infrared measurements have so far not been able to resolve the issue of whether the predominant source of the dust is cometary or asteroidal. The coronal imager experiment, combined with tomographic analysis made possible by the range of viewpoints available along the spacecraft trajectory, will for the first time determine the small-scale, three-dimensional structure of the optical corona and allow detailed comparisons with the simultaneously obtained in situ measurements. The coronal imager data, combined with simultaneous coronagraph data from Earth, will also provide sensitive and precise measurements of the large-scale structure of the corona; this structure is important to the interpretation of other data measured aboard Solar Probe concerning the outflow and acceleration of the solar wind.

Is there a potential for revealing previously unknown phenomena, processes or interactions?

This mission is exploratory, and nature has always provided major surprises on previous exploratory missions, often overturning previously accepted ideas. Although much had been known about the outer planets from telescopic observations, Voyager revolutionized our understanding of their structure and environments. Solar Probe should provide similar surprises. Anticipating the unknown is speculative, but we can expect major upheavals in our understanding of turbulence in the solar atmosphere, the particle acceleration processes occurring in the corona and the very nature of the processes that produce the corona itself.

In what ways will the mission answer fundamental questions or stimulate theoretical understanding of fundamental structures or processes related to the origins and evolution of the universe, the solar system, the planet Earth or life on Earth?

Stellar coronae and winds are common in nature. They are intimately tied through magnetic activity to the interior of the star and are strongly related to the convective zones throughout the life of a star. However, the interconnections between these phenomena are presently poorly understood. Because the Sun is an ordinary class G star that shares many properties in common with a wide class of other main-sequence stars having well-developed convection zones, a deeper understanding of the link among the Sun's magnetic activity, coronal heating and solar wind expansion could be used to refine models that fit observations of general stellar magnetic activity and related stellar coronae.

Accretion disks around black holes and in active binary systems containing compact stellar objects contain highly turbulent plasmas, presumably acting as magnetohydrodynamic dynamos. Magnetic bouyancy leads to the escape of magnetic field from the interior of the disk, much as magnetic field rises from the solar interior. The resulting outflow of a plasma wind from the disk is presumably due to magnetohydrodynamic waves and magnetic reconnection, as is the solar wind outflow. Discovery and investigation of the mechanisms driving the solar wind flow may provide useful insights into the ejection of material from accretion disks.

Cosmic dust is known to play an important role in the life cycle of stellar systems. Our solar system provides a laboratory to study one such star to obtain detailed understanding of the chain of events and their causative mechanisms. The sequence of stages in this process links gas and dust accumulation from the interstellar medium to form the present solar system and the dissolution of objects via solar heating (comets) or collisional breakup (asteroids, moons, planets) again into gas and dust. The dust created within the solar system supplies the zodiacal dust cloud; dust is also lost to the interstellar medium as beta meteoroids.

In what ways will the mission advance understanding of important and widely occurring natural processes and stimulate modeling and theoretical description of those processes?

A possible explanation of a hot magnetically open corona is that many small magnetic reconnection events in the solar atmosphere release sufficient energy to heat the corona. The energy supply for the reconnection events is the emergence of small bipolar magnetic regions carried upward from beneath the surface. Observations of the resultant plasmoids and jets, and their consequent collisional slowing and heating, will help stimulate and refine theoretical models of the open corona. The mission will also be important for the development of MHD and plasma turbulence theory. Computer simulation and theoretical analyses are the two primary tools presently used to approach this problem. We expect the Solar Probe to provoke increased research and new results in this area.

Is there a potential for discovering new laws of science, new interpretations of laws or new theories concerning fundamental processes?

New theories of nonlinear wave evolution, nonlinear wave–particle interactions and the consequent stochastic energization of particles are likely to result from the findings of Solar Probe. These findings generally can be applied to stellar envelopes.

I.D. Uniqueness

What are the special reasons for proposing this investigation as a mission in space? Are there other ways that the desired information could be acquired?

The mission is unique in that the region of the corona inside 0.3 AU, and parts of the out-of-the-ecliptic heliosphere, will be explored for the first time. Within 1 AU of the Sun, the spacecraft is at moderate and high latitudes in the heliosphere; the only previous high latitude observations will have been those obtained by Ulysses at distances of 2.5 AU and greater. No previous solar wind explorations have travelled within 0.3 AU of the Sun (the perihelion of HELIOS). However, observations in the region from the sonic point (between 2 and 6 solar radii) to beyond the outer distance of strong plasma turbulence as indicated by the radio scintillation measurements (about 35 solar radii) are essential for understanding the extended coronal heating known theoretically to play an important role in solar wind acceleration. The conditions within this region can be determined using no known technique other than in situ observations such as will be afforded by the Solar Probe.

Is there a special requirement for launching the mission on a particular time schedule?

Flight opportunities for the Solar Probe typically occur at 13-month intervals.

II. Programmatic Considerations

II.A. Feasibility and Readiness

Is the mission technologically feasible?

The spacecraft concept is based on high inheritance from the Mariner Mark II program (a.k.a. CRAF/Cassini or C/C). Most of the C/C subsystems have more than sufficient performance for the Solar Probe mission. Other than repackaging the system, the unique item for this mission is the thermal shield. Over 10 years of research have gone into developing this shield concept not only at JPL but also in U.S. industry and overseas. The result is a shield made of a lightweight material (carbon–carbon) expected to perform well at the perihelion of 4 solar radii (~2100 K) with minimum mass loss (less than 2.5 mg/sec). Carbon–carbon is a unique material that actually increases in tensile strength with temperature. It has been utilized in large structures (the leading edge of the space shuttle, the nozzle of the Minuteman missile) and in high-temperature shield applications (spacecraft and reactor shields) for many years. It is therefore a mature, commercially available technology. The plasma wave antennas will also be made of this material.

Technologies to be inherited from the C/C mission include the RTGs (radioisotope thermoelectric generators) design and implementation process, the Ka-band telecommunications system and the data handling and storage subsystems. The RTGs will supply the spacecraft power. Multiple studies have demonstrated that solar-dependent power would be very complex and unreliable for the range of solar distances of 5 AU to 0.019 AU (4 solar radii). Minor developments to the Solar Probe RTGs have been analyzed by the Department of Energy, including the placement of a reflector on one side of the RTG to radiate heat away from the spacecraft umbra. Thermal analysis indicates this will be quite effective. Using Ka-band telecommunications will reduce solar coronal scintillation effects when Solar Probe is near perihelion. This hardware development will be completed for the CRAF/Cassini Project and the Solar Probe can inherit this directly. The state-of-the-art central computer and data handling subsystem will also be directly inherited from CRAF/Cassini as well as the solid-state data storage unit. The modular design of the CRAF/Cassini spacecraft allows reconfiguration to fit the mechanical constraints of Solar Probe.

Another consideration in the spacecraft design is the near-solar dust environment. Infrared photometric observations indicate that there are circumsolar equatorial rings of dust between 4 and 10 solar radii that seem to be composed of a refractory (silicate?) material. The rings may or may not be relatively stable over time. The implication for the Solar Probe is that the spacecraft will approach the rings from its high inclination orbit at a speed of over 300 km/sec. Depending on the actual distribution and velocities of the particles, the spacecraft-dust relative speed could be over 400 km/sec. Preliminary investigations into spacecraft shielding for this dust environment suggest that the typical multilayer thermal insulation (MLI) blankets used on interplanetary spacecraft would be the initial choice for "bumper" shields against the dust. The standoff distance from the spacecraft to the outer layers of the MLI blankets will be larger than normal, and